

11-34
172859

NASA Technical Memorandum 106206

Application of Ray Tracing in Radiation Heat Transfer

Joseph F. Baumeister
Lewis Research Center
Cleveland, Ohio

Prepared for the
Computer Applications Symposium
cosponsored by the ASME and LMU
Los Angeles, California, March 12, 1993
and
Thermal and Fluids Analysis Workshop
sponsored by NASA Lewis Research Center
Cleveland, Ohio, August 16-20, 1993



(NASA-TM-106206) APPLICATION OF
RAY TRACING IN RADIATION HEAT
TRANSFER (NASA) 52 D

N93-29075

Unclass

G3/34 0172859

Application of Ray Tracing in Radiation Heat Transfer

Joseph F. Baumeister
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Summary

The objectives behind ray tracing as compared to other analytical techniques are to achieve the greatest accuracy in model representation and solution, while minimizing computer resources and computational time. Ray tracing programs can give the user enhanced capabilities based on performance, accuracy and flexibility to solve both simple and complex problems. This collection of presentation figures displays the capabilities of ray tracing for radiation propagation calculations as compared to an analytical approach. The goal is to introduce the terminology and solution process used in ray tracing, and provide insight into radiation heat transfer principles and analysis tools. A thermal analysis working environment is introduced that solves demanding radiation heat transfer problems based on ray tracing. Various model generating techniques, model conversion capabilities, and graphical preprocessing and postprocessing are discussed. These programs are personal-computer based, but include the ability to solve large problems on a mainframe or super computer. This information may serve as a reference for designing and building one's own analysis environment.

Introduction

Applying computer models and numerical approaches to evaluate the emission and propagation of multiple reflecting radiation can be an involved process for both simple and complex geometries. Depending on surface geometry and thermophysical properties, radiant energy propagation can include reflecting, transmitting, and absorbing energy. Following the propagation of energy becomes an enormous problem as the complexity of the geometry and thermophysical properties increase. Currently, there are a variety of computer programs and simplifying analytical techniques used to analyze radiation as it propagates. Each solution procedure has advantages and disadvantages based on the fundamentals of physics, modeling requirements and limitations, computer requirements and limits, and solution convergence requirements.

This collection of figures displays the capabilities of ray tracing for radiation propagation calculations as compared to an analytical approach. A major motivation behind using ray tracing is to incorporate a highly accurate analysis technique for use in a variety of radiation heat transfer problems. A thermal analysis working environment is introduced that solves demanding radiation heat transfer problems based on ray tracing. This analysis working

environment takes advantage of existing personal computer tools to solve simple and advanced radiation heat transfer problems. This provides the user a flexible environment for developing thermal design experience and engineering judgment through analysis experimentation, while minimizing computer resources. The user still maintains the ability to solve more computer intense problems on a mainframe or super computer.

Symbols

A	surface area
B	radiation interchange factor
C_1, C_2	Planck's spectral energy distribution constants
C_0	speed of light in vacuum
e	emissive power
E	emissive energy per unit time
F	view factor
h	Planck's constant
i	radiant intensity per unit area
I	radiant intensity
k	Boltzmann constant
n	nth surface
r	radius distance
T	absolute temperature
σ	Stefan-Boltzmann constant
ϵ	emissivity
θ	polar angle
ϕ	circumferential angle
Γ	emissive power fraction in spectral region
δ	identity matrix
λ	wavelength (vacuum) in micrometer (μm)

Superscript

/ directional quantity

Subscripts

A	of surface A
b	blackbody
i, j	ith and jth surfaces
λ	spectrally dependent wavelength
∞	infinity

THE OBJECTIVE AND AGENDA

The objective figure provides a focus to the intent and goal behind the presentation. This figure also introduces the ray tracing subject matter and items discussed.

The agenda figure provides the topics discussed in the following sets of figures. A variety of topics are discussed for an overview of ray tracing characteristics and advantages. The radiation background section provides preliminary information on the principles of radiation heat transfer. Ray tracing is also applied to other areas, such as lasers, optics, and light propagation. A comparison between an analytical technique and ray tracing is presented. A ray tracing based thermal radiation solution environment is introduced which operates on a personal computer. This solution environment displays the capabilities and flexibility available to users. Example models and results are provided in a computer demonstration. This includes graphically watching ray bouncing in several computer generated animations. An introduction to the physics behind ray tracing is also provided.

APPLICATION OF RAY TRACING IN RADIATION HEAT TRANSFER

OBJECTIVE:

- **SUPPLY GENERAL RADIATION HEAT TRANSFER INFORMATION**
- **INTRODUCE RAY TRACING APPLIED TO RADIATION HEAT TRANSFER**
- **RESPOND TO SPECIFIC QUESTIONS RELATED TO RAY TRACING HEAT TRANSFER**
- **INTRODUCE A RAY TRACING PROCEDURE USED AT LEWIS RESEARCH CENTER**
- **DISCUSS PRE AND POST PROCESSING OPTIONS**
- **DISPLAY RAY TRACING GRAPHICS**

AGENDA

- **RADIATION BACKGROUND**
- **RADIATION INTERCHANGE ANALYSIS TECHNIQUES**
- **ADVANCED RAY TRACING APPLICATIONS**
- **RAY PHYSICS**
- **A RAY TRACING PROCEDURE USED AT LEWIS RESEARCH CENTER**
- **COMPUTER DEMOS**
- **INTRODUCTION TO RAY TRACING PROGRAMS**
- **SUMMARY**

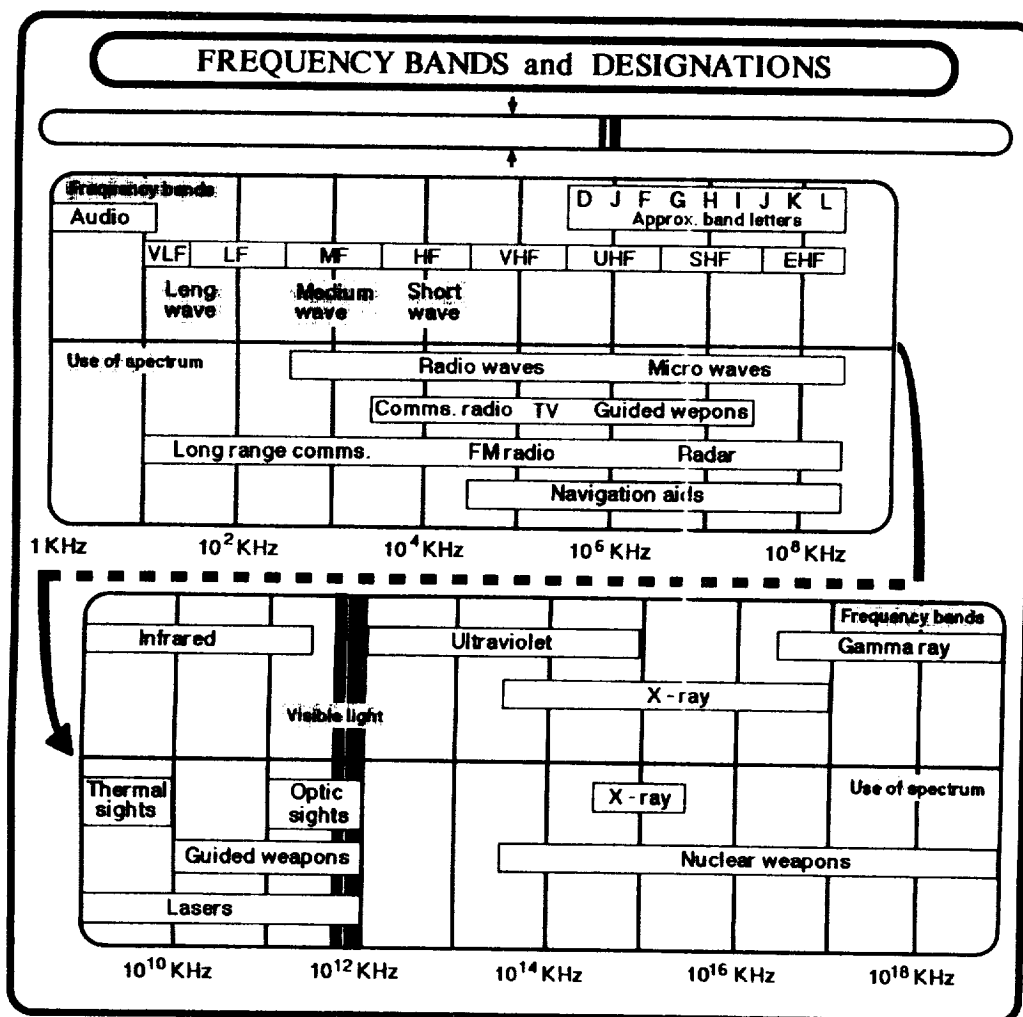
RADIATION BACKGROUND SECTION

This section supplies background information on radiation principles and typical radiation heat transfer calculations. The nature of infrared (IR) radiation forms are introduced and discussed in relation to the electromagnetic spectrum. The effects of radiation attenuation are also shown by comparing the radiation propagation in the atmosphere as compared to space (vacuum). The basic definitions, equations, units, and notation used to define radiation characteristics were selected from reference 1. Appendix A supplies additional background information on radiation heat transfer concepts.

General equations for both blackbody and non-blackbody radiation are shown. These equations shown total hemispherical emitted energy and radiation exchange between surfaces. Radiation exchange between surfaces require terms that define the amount of radiation that leaves one surface and is absorbed by another surface directly and indirectly. The geometric relationship that defines the radiation exchanged between blackbody surfaces, (perfect emitters and absorbers), are called geometric configuration factors or view factors. The view factor for blackbody isothermal surfaces is the fraction of emitted radiant energy leaving a surface i that reaches another surface j . Since both surfaces are blackbodies or perfect absorbers of radiant energy, no reflected energy is introduced into the view factor value, F_{i-j} . For simple geometric configurations, various view factor references are available. For complex geometric configurations, various computer techniques have been developed where surfaces are defined, and mathematical or ray tracing techniques are applied to solve the surface relationships.

For non-blackbody surfaces the blackbody view factor is replaced by the radiation interchange factor, B_{i-j} , which represents real surface radiation exchange. The radiation interchange factor is the fraction of emitted energy by a real surface i that is absorbed by real surface j , including all reflections from other real surfaces including the emitting surface i . This is where the B_{i-j} term defines the relationship between the energy emitted from surface A_1 that is absorbed by surface A_2 directly and indirectly. This indirect radiant energy may result from multiple reflecting energy between A_1 and A_2 , and energy from A_1 that is reflected from other surfaces to A_2 . The radiation path for a multiple surface configuration may include all surfaces, which can result in a large number of total non-blackbody emitted energy terms. Computer programs are also available to calculate B_{i-j} values.

RADIATION BACKGROUND

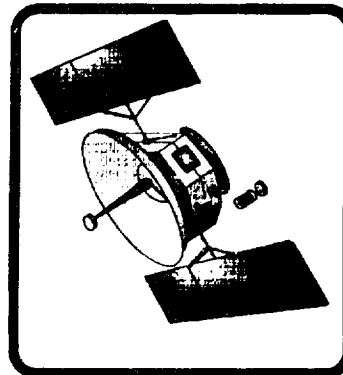
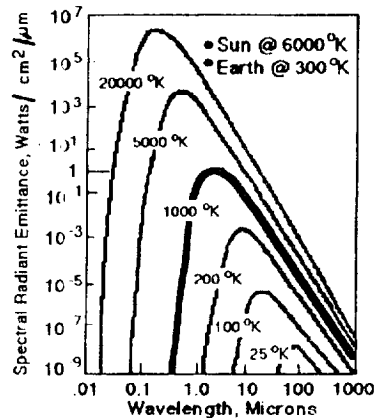


BACKGROUND THERMAL RADIATION

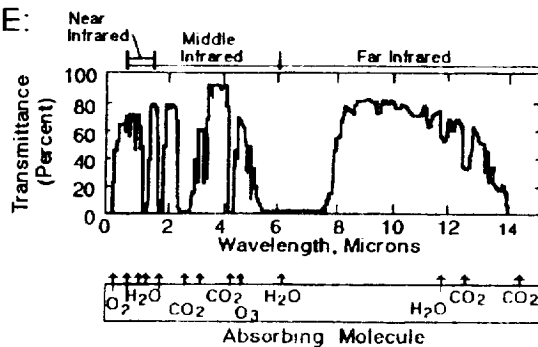
- ALL SURFACES WITH TEMPERATURES ABOVE ABSOLUTE ZERO EMIT ELECTROMAGNETIC RADIATION
- THERMAL INFRARED (IR) RADIATION FORMS:
 - ROTATION OF MOLECULES (FAR IR BAND)
 - VIBRATION OF ATOMS WITHIN MOLECULES (MIDDLE TO FAR IR BAND)
 - ELECTRON TRANSITION (NEAR IR BAND, VISIBLE, ULTRAVIOLET BAND)
- EMITTED RADIATION IS A FUNCTION OF SURFACE THERMOPHYSICAL PROPERTIES AND TEMPERATURE

BACKGROUND Space VS. Atmosphere Attenuation

SPACE:



ATMOSPHERE:



BACKGROUND GENERAL EQUATIONS

BLACKBODY HEMISPHERICAL EMISSIVE POWER, (Planck's Law):

$$e_{\lambda b}(\lambda, T) = \pi i'_{\lambda b}(\lambda, T) = \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \left[\frac{BTU}{hr \mu m ft^2} \right]$$

TOTAL BLACKBODY HEMISPHERICAL EMISSIVE POWER:

$$e_b(T) = \int_0^\infty e_{\lambda b} d(\lambda) = \int_0^\infty \pi i'_{\lambda b} d(\lambda) = \int_0^\infty \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda) = \sigma T_A^4 \left[\frac{BTU}{hr ft^2} \right]$$

TOTAL NON-BLACKBODY HEMISPHERICAL EMITTED ENERGY:

$$E_{A_1}(T_A) = \int_0^\infty A_1 e_{\lambda b}(\lambda) d\lambda = A_1 e_A \sigma T_A^4 \left[\frac{BTU}{hr} \right]$$

BACKGROUND RADIATION EXCHANGE BETWEEN SURFACES

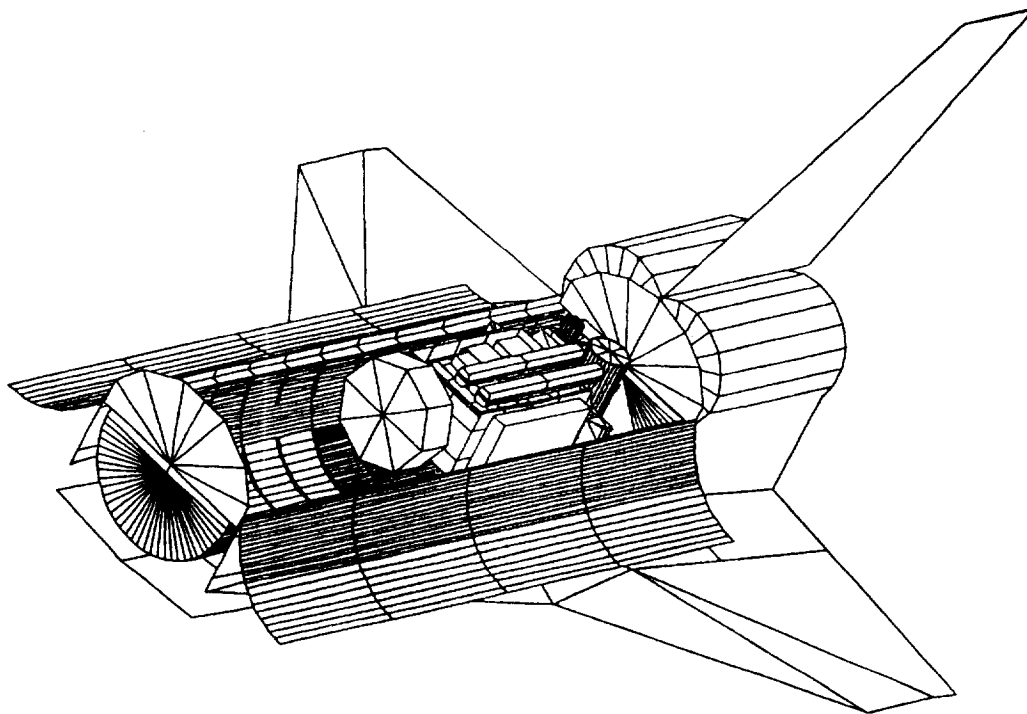
TOTAL BLACKBODY EMITTED ENERGY:

$$E_{b A_1 - A_2}(T_A) = A_1 F_{A_1 - A_2} \sigma (T_A^4) \left[\frac{BTU}{hr} \right]$$

TOTAL NON-BLACKBODY EMITTED ENERGY:

$$E_{A_1 - A_2}(T_{A_1}) = A_1 B_{A_1 - A_2} e_{A_1} \sigma T_{A_1}^4 \left[\frac{BTU}{hr} \right]$$

EXAMPLE OF MULTIPLE SURFACE RADIATION PATHS



BACKGROUND WAVELENGTH BANDS

NON-BLACKBODY EMITTED ENERGY WITHIN A WAVELENGTH BAND:

$$E_{A_1-A_2}(\lambda_1 T - \lambda_2 T) = \epsilon_{A_1} A_1 B_{A_1-A_2} \int_{\lambda_1}^{\lambda_2} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda)$$

APPLYING A NUMERICAL POLYNOMIAL CURVE FIT:

$$E_{A_1-A_2}(\lambda_1 T - \lambda_2 T) = \epsilon_{A_1} A_1 B_{A_1-A_2} [\Gamma_{0-\lambda_2 T_{A_1}} - \Gamma_{0-\lambda_1 T_{A_1}}] \sigma T_{A_1}^4 \left[\frac{BTU}{hr} \right]$$

WHERE $\Gamma_{0-\lambda T}$:

$$\Gamma_{0-\lambda T} = \frac{15}{\pi^4} \sum_{n=1}^{\infty} \left[\frac{e^{-nx}}{n} \left(x^3 + \frac{3x^2}{n} + \frac{6x}{n^2} + \frac{6}{n^3} \right) \right]$$

$$\text{where } x = \frac{C_2}{\lambda T}$$

RADIATION INTERCHANGE ANALYSIS TECHNIQUES

As shown in the Radiation Background section, the radiation interchange between surfaces requires the geometric and thermophysical property relationships. Currently there are two applied radiation interchange analysis techniques in wide use. The first is what we call, for comparison, the analytical approach and the second the ray tracing approach. The following figures briefly explain the principles behind the approaches, and their advantages and disadvantages.

RADIATION INTERCHANGE ANALYSIS TECHNIQUES

ANALYSIS TECHNIQUES

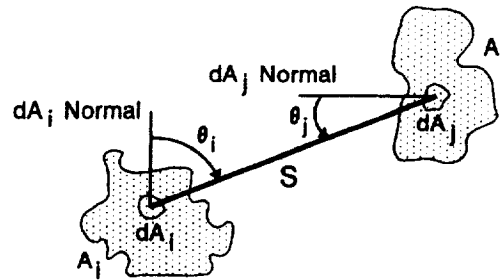
CURRENT RADIATION HOT PARTS ANALYSIS TECHNIQUES:

- ANALYTICAL APPROACH
- RAY TRACING APPROACH

ANALYTICAL APPROACH

VIEW FACTORS:

$$F_{i-j} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi S^2} dA_j dA_i$$



RADIATION INTERCHANGE FACTORS:

$$B_{k-i} = [\epsilon_k A_k] [F_{k-j}] [\delta_{ij} - (1 - \epsilon_j) F_{i-j}]^{-1} [\epsilon_i]$$

ANALYTICAL APPROACH ADVANTAGES AND DISADVANTAGES

ADVANTAGES:

- FAST
- COMMONLY USED ANALYSIS TECHNIQUE

DISADVANTAGES:

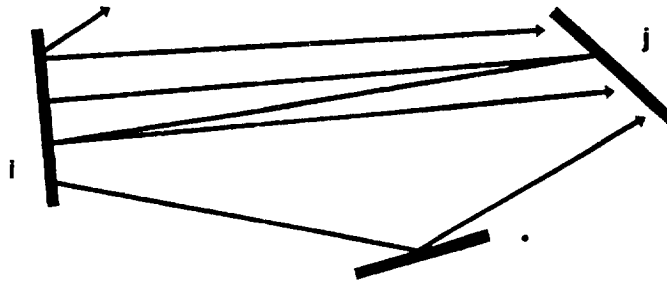
- UNIFORM NODE SURFACE TEMPERATURE AND THERMOPHYSICAL PROPERTIES
- ENERGY EMITTED AND REFLECTED DIFFUSELY
- UNIFORM NODE INCIDENT FLUX
- UNIFORM NODE REFLECTED FLUX

RAY TRACING APPROACH

- STATISTICAL NUMERICAL METHOD
- MATHEMATICAL RAYS ARE USED TO SIMULATE RADIATION EMITTED AND REFLECTED FROM SURFACES
- % OF INCIDENT AND ABSORBED ENERGY CAN BE APPLIED TO ENERGY BALANCE EQUATION

RADIATION INTERCHANGE FACTORS:

- FRACTION OF EMITTED ENERGY BY A REAL SURFACE i THAT IS ABSORBED BY REAL SURFACE j , INCLUDING ALL REFLECTIONS FROM OTHER REAL SURFACES INCLUDING THE EMITTER SURFACE i .



RAY TRACING APPROACH ADVANTAGES AND DISADVANTAGES

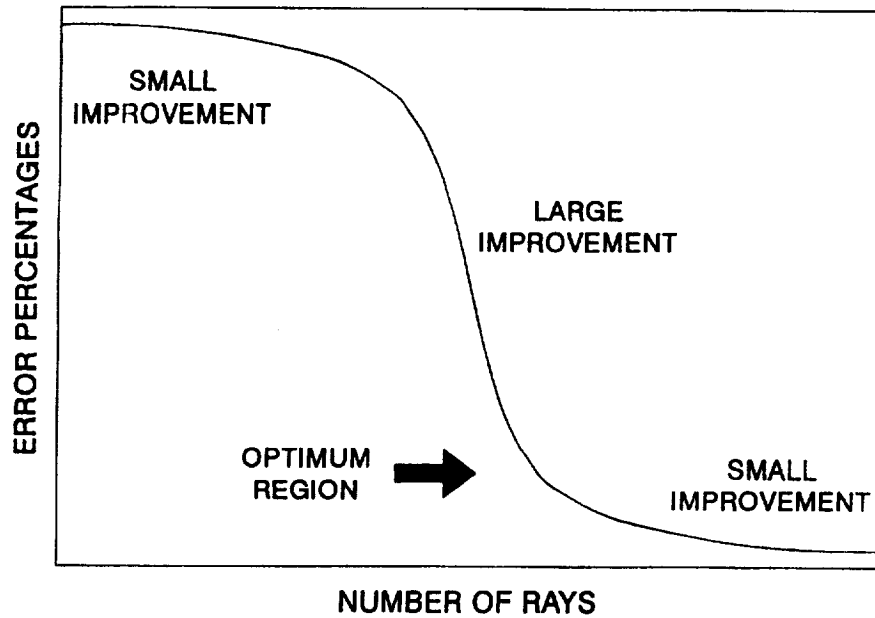
ADVANTAGES:

- DIFFUSE OR SPECULAR REFLECTANCE (% SPECULARITY)
- REFRACTION
- ABSORBING MEDIA
- REFRACTION
- SURFACE PROPERTIES AS A FUNCTION OF ANGLE OF INCIDENCE
- BI-DIRECTIONAL REFLECTIONS
- DIRECT AND REFLECTED SOLAR, ALBEDO, PLANETARY RADIANT ENERGY

DISADVANTAGES:

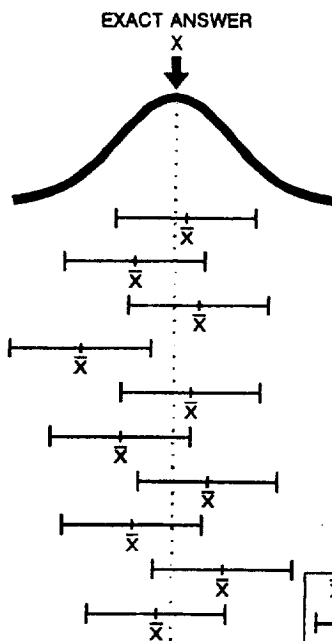
- UNIFORM NODE SURFACE TEMPERATURE AND THERMOPHYSICAL PROPERTIES
- POSSIBLE LONGER COMPUTER RUN TIME

GENERAL CONCEPT BEHIND THE NUMBER OF EMITTED RAYS ON ERROR PERCENTAGES

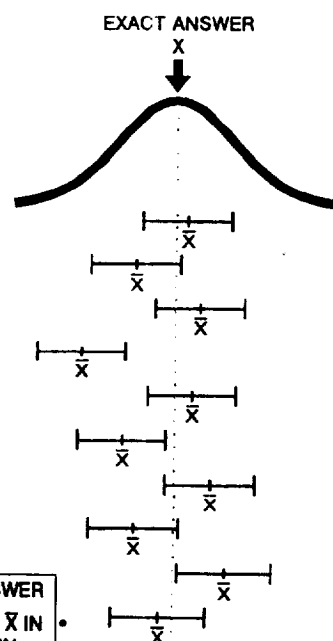


GENERAL CONCEPT BEHIND CONFIDENCE LEVELS

90% CONFIDENT LEVEL



70% CONFIDENT LEVEL



\bar{x} - CALCULATED ANSWER
 ——— - ERROR BAND FOR \bar{x} IN GIVEN SAMPLE RUN

ADVANTAGES OF GRAPHICAL RAY TRACING OUTPUT

GRAPHICAL RAY TRACING PROVIDES:

- VISUALIZATION FOR RESULTS INTERPRETATION
- VISUAL EFFECTS OF SURFACE THERMOPHYSICAL PROPERTIES
- LOCATIONS OF POSSIBLE HOT SPOTS
- NEED TO REDEFINE SURFACE SECTIONING
- REVEAL MISALIGNMENT OF MODELED SURFACES (GAPS BETWEEN SURFACES)

SEVERAL GRAPHICAL RAY TRACING FEATURES:

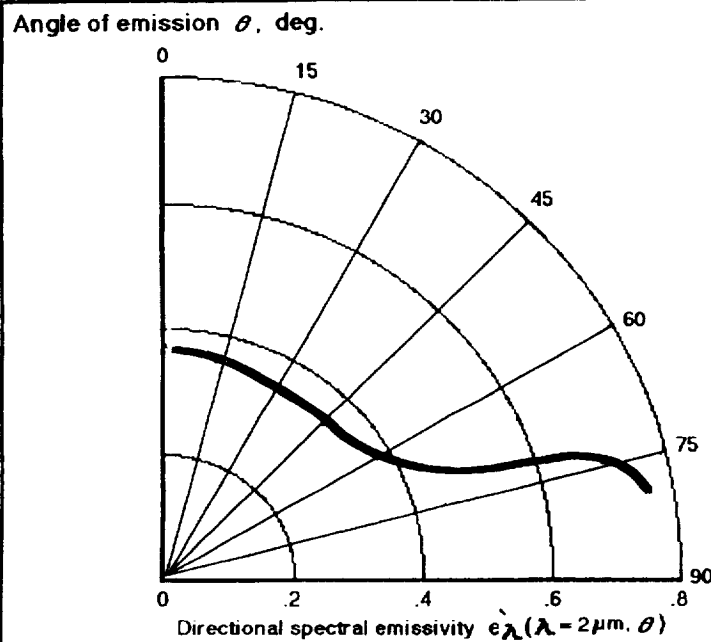
- EVALUATE EMITTED AND REFLECTED RAY DISTRIBUTIONS
- LOCATE REFLECTED RAYS
- LOCATE ESCAPED RAYS
- LOCATE TERMINATED RAYS

ADVANCED RAY TRACING APPLICATIONS

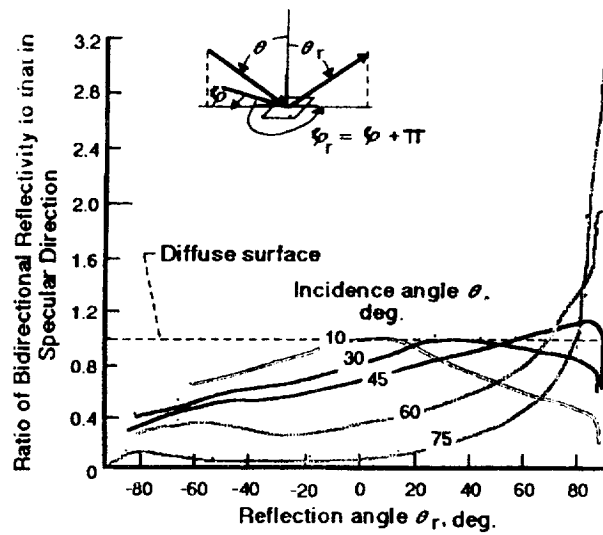
This section display how surfaces thermophysical properties may have non-uniform characteristics. Directional spectral emissivity, and bidirectional reflectivity are two example cases where ray tracing has advantages. In ray tracing, the ray propagation from emissions and reflections can easily be adjusted from imputed thermophysical properties tables. Even grooved surfaces could be modeled in a variety of ways using tabular input, resulting in simplified models.

ADVANCED RAY TRACING APPLICATIONS

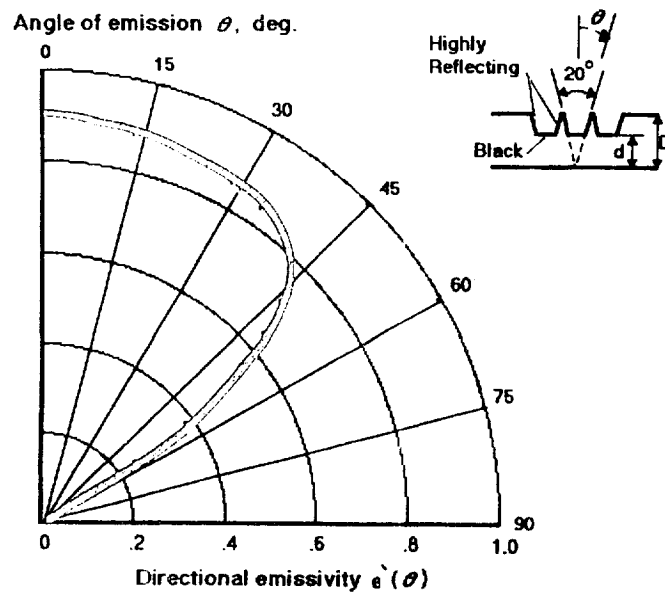
Directional Spectral Emissivity As a Function of Angle



Bidirectional Reflectivity



Simulate and Evaluate Complex Surface Geometries



RAY PHYSICS

The general principles governing the use of ray tracing to simulate radiation propagation are characterized by several ray propagation phenomena. The following figures provide an introduction to the phenomena used in ray tracing. Further information regarding these figures can be obtained from reference 8.

RAY PHYSICS

RAY PHYSICS WAVE PHENOMENA

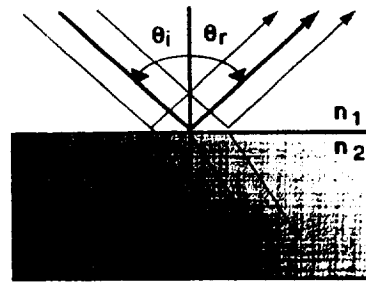
- **ABSORPTION**
ENERGY IN THE WAVE IS CONVERTED INTO HEAT WITHIN A MEDIUM.
- **REFLECTION**
SCATTERING OF INCIDENT WAVE ENERGY THAT IS REFLECTED FROM A SURFACE.
- **TRANSMISSION**
PASSAGE OF A WAVE THROUGH A MEDIUM.
- **DIFFRACTION**
BENDING OR DIFFUSE SCATTERING OF A WAVE AROUND A RELATIVE SHARP EDGE.
- **REFRACTION**
BENDING OF A WAVE AS IT PROPAGATES ACROSS A BOUNDARY BETWEEN TWO MEDIUM WITH DIFFERENT VELOCITIES OF PROPAGATION.
- **INTERFERENCE**
VECTORIAL ADDITION OF TWO OR MORE WAVES.

RAY PHYSICS

ABSORPTION, REFLECTION, TRANSMISSION



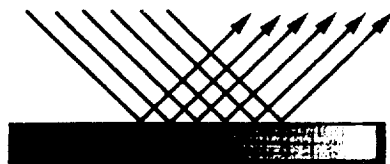
Wave representation



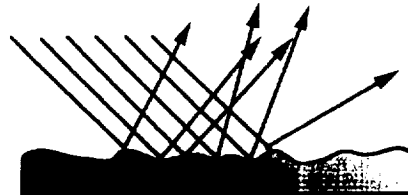
Ray representation

RAY PHYSICS

REFLECTION

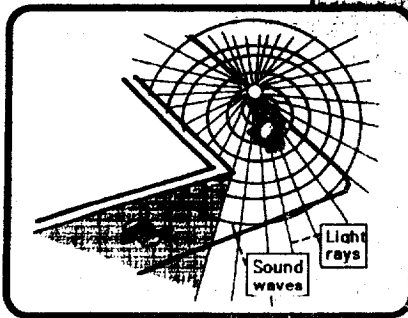
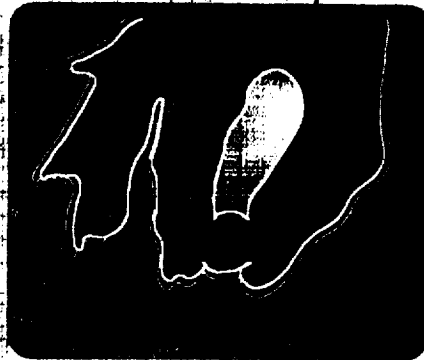
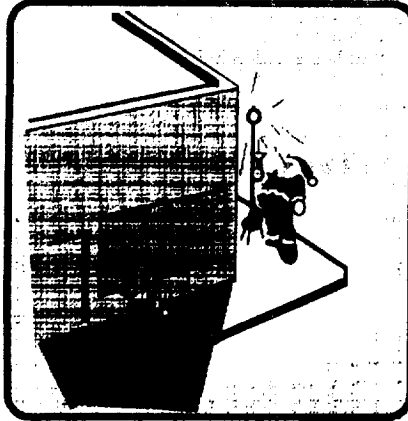


Specular Reflection

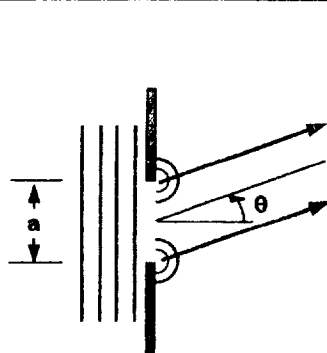


Diffuse Reflection

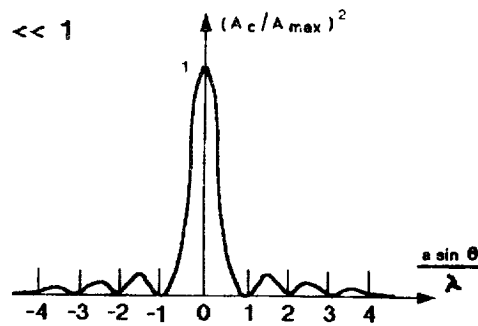
RAY PHYSICS DIFFRACTION



RAY PHYSICS NEGLECTING DIFFRACTION

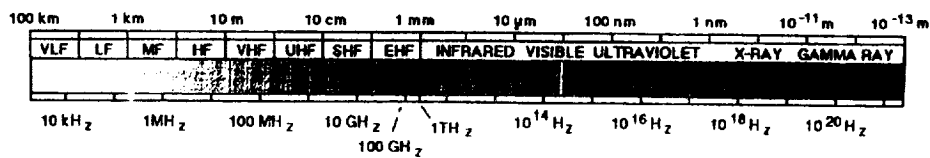


$$\frac{\lambda}{a} \ll 1$$



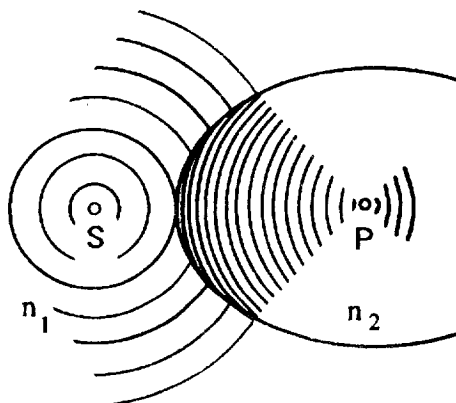
Intensity pattern for diffraction by a uniform slit of width a .

WAVELENGTH (in air)

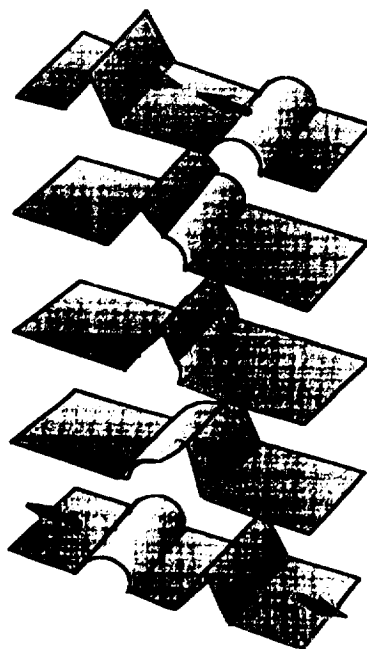


FREQUENCY

RAY PHYSICS REFRACTION



RAY PHYSICS INTERFERENCE SUPERPOSITION OF RAYS



A RAY TRACING PROCEDURE USED AT LEWIS RESEARCH CENTER

Using a ray tracing technique to solve a variety of problems can be enhanced by incorporating other computer programs. The thermal user may also be required to use various other programs for model and solution graphics, model conversion, and plotting results. Dealing with these analysis tools while retaining the flexibility to transfer data between them can be a problem. The NASA Radiation Identification Program (NAS-RID) combines a variety of computer programs to solve radiation problems. This environment provides the user enhanced analysis capabilities to solve both simple and complex programs. The computer programs that comprise the NAS-RID environment were selected based on performance, accuracy and flexibility. The design of the NAS-RID environment (shown in the third and fourth figures in this section), was to maintain a non-rigid or open environment while maintaining data transfer between programs. This includes linking structural finite element models with heat transfer geometric math models. This environment was also designed so programs could be added or substituted based on user requirements. It was also desired that NAS-RID run on a personal-computer (PC) or components on a mainframe or super computer. The following are brief descriptions of the computer codes that comprise or support NAS-RID. Appendix B supplies information that defines the use of the term "model" in an analysis.

NEVADA Code

The Net Energy Verification and Determination Analyzer program, called NEVADA (ref. 2), is a software package consisting of several programs in which a Monte-Carlo mathematical technique is applied to radiation propagation. The NEVADA program was attractive to use because of its ability to model the complex laws of physics associated with radiation propagating from various geometry defining surface types and thermophysical properties. In the NEVADA code, a statistical numerical method using the Monte-Carlo technique is applied to a ray tracing procedure to model radiation exchange. The ray tracing procedure mathematically traces emitted rays (simulating emitted radiation) as they propagate. Each ray leaving a surface is considered a bundle of photons that carries equal, discrete, amounts of energy. The path of the bundles (rays) may interact with various surfaces, which may reduce the energy level of the bundle. The interacting surfaces may have different thermophysical properties and geometric configurations that affect the propagation of each bundle differently. By accounting for all the emitted bundles as they propagate, percentages of incident and absorbed energy at different locations can be computed. The percentages of absorbed energies (radiation interchange factors) are then applied to the energy balance equations.

Generally NEVADA is used to solve two types of problems; radiation interchange factors and environmental radiant heating sources. Typical environmental radiant heating sources (solar, albedo, and earthshine) on a satellite are calculated for each modeled surface at various points in an orbit. The NEVADA program also supplies a plotting package for model and orbit verification. NEVADA is an industry standard code used in predicting radiation interchange factors and environmental radiant heating sources. Various documented uses and results are published throughout literature. Verification of the numerical ray tracing technique within the NEVADA program for use in studying cavity radiation propagation is discussed in reference 3, where isothermal and non-isothermal gray-diffuse cylindrical geometries with uniform surface emissivity values were evaluated and compared with known solutions.

FEMAP Code

FEMAP stands for Finite Element Modeling and Postprocessing Program (ref. 4). FEMAP is a menu-driven computer program for designing and building finite element models and a postprocessing tool for the personal computer user. FEMAP is designed to access many popular finite element programs by translating the FEMAP generated models to the desired structural analyzer format, and postprocess structural analyzer results within FEMAP. FEMAP provides a variety of mesh generation and manipulation techniques for model generation. It contains graphic visualization options for displaying models and results to the computer screen or printing devices. It also provides the user with tools for generating and displaying contoured types of plots and animation features.

NAS-CONV (Model Conversion)

NAS-CONV is a FORTRAN program that stands for NASA Convert Program. This program allows one to convert to and from the NEVADA geometric model format and the FEMAP finite element model. This program also converts a variety of other specific file formats into a FEMAP model. The purpose of the NAS-CONV program is to help speed up the geometric model generation process by converting existing structural models into the required NEVADA format. It also has the ability to display geometric model results using the structural model visualization techniques inherent in FEMAP. Currently this model converts three surface types, triangular plate, quadrilateral plate, and finite element line elements into NEVADA cylinder elements.

NEVTRACE

NEVTRACE is a FORTRAN program that stands for NEVADA Ray Tracing Program. The NEVADA ray tracing results are read into NEVTRACE and are modified based on selected options for graphic visualization of the rays being traced. The user can define various options for selecting number of rays, types of rays, and groups of rays for graphing. The NEVTRACE program generates a formatted data set that is displayed within the FEMAP model. By formatting the ray tracing data for input into the FEMAP model, FEMAP graphical features can be used to display the results.

By graphically viewing NEVADA ray tracing results, one can evaluate features like the distribution of emitted rays on a surface, location of reflected rays, where rays have escaped to the surroundings, and location of terminated rays. Depending on the selected NEVTRACE options, graphical visualization can provide locations of possible hot spots, need to redefine surface sectioning, misalignment of surfaces (gaps between surfaces), and the distribution of reflected rays as defined by physical surface properties.

TRACK-E

The Track Energy Procedure or "TRACK-E" is a FORTRAN program used to evaluate the energy propagation between defined surface nodes. The TRACK-E program calculates and sums the surface energy emitted and absorbed through the radiation conductor values (term used to represent the energy flow paths between separated surfaces). The radiation conductors incorporate the NEVADA radiation interchange factors. The TRACK-E program can also modify the radiation conductor values to include wavelength band evaluation of the IR spectrum. If the NEVADA model includes spherical or hemispherical surfaces that enclose the model, TRACK-E can then be used to evaluate the total and component energy distribution using energy per solid angle calculations. Appendix A defines the general radiation exchange equation solved in the TRACK-E program with the radiation interchange factors. The user can also evaluate radiant energy calculations for individual surfaces by entering radiation interchange factors, areas, emissivities, and temperatures. The program also tabulates the emitted and absorbed energy from each surface. The results from TRACK-E can be formatted for input into a FEMAP model for color visualization of the solutions.

By designing NAS-RID to work with various other programs, NAS-RID can take advantage of existing tools to enhance its analysis capabilities. NAS-RID was designed to use the capabilities in the

following programs. These programs are of great value, but exclusion will not limit ones analysis ability.

TRIF

The Thermal Radiation Interchange Format program (ref. 5), called TRIF, is used to translate to and from various radiation analyzer program formats. This code provides the ability to convert several radiation interchange code formats into a NEVADA format.

LAVA

LAVA (ref. 6) is a PC based program that graphically displays a NEVADA model with various model and orbit viewing options. LAVA can interactively display the NEVADA model for use in validating surface generation and orbit characteristics. It also gives one the ability to analyze and manipulate orbital dynamics interactively from various model and orbital viewpoints. One option provides the user with an animation effect describing the satellite motion in space with its relationship to the earth and sun. This program uses the NEVADA format for both the model surfaces and orbit descriptions.

SINDA

The System Improved Numerical Differencing Analyzer (ref. 7), called SINDA, is a generalized thermal analysis program. The program solves lumped parameter representations of physical problems governed by diffusion-type equations as a resistor-capacitor (R-C) network that represents a thermal system. The SINDA thermal model includes the NEVADA radiation conductors from the TRACK-E program, node thermal capacities, and the conduction network. Various solution routines can be selected plus a variety of programming options and procedures. Presently the PC version of the SINDA program is supplied with the PC version of NEVADA.

LOWTRAN

LOWTRAN (ref. 8) is currently not included in the NAS-RID environment, but NAS-RID is structured to accommodate the mainframe or PC version of LOWTRAN. LOWTRAN is a computer program that calculates atmospheric transmittance and background radiance for a given atmospheric path at low spectral resolution. Spherical or hemispherical energy from the TRACK-E program could be modified for direct input into LOWTRAN.

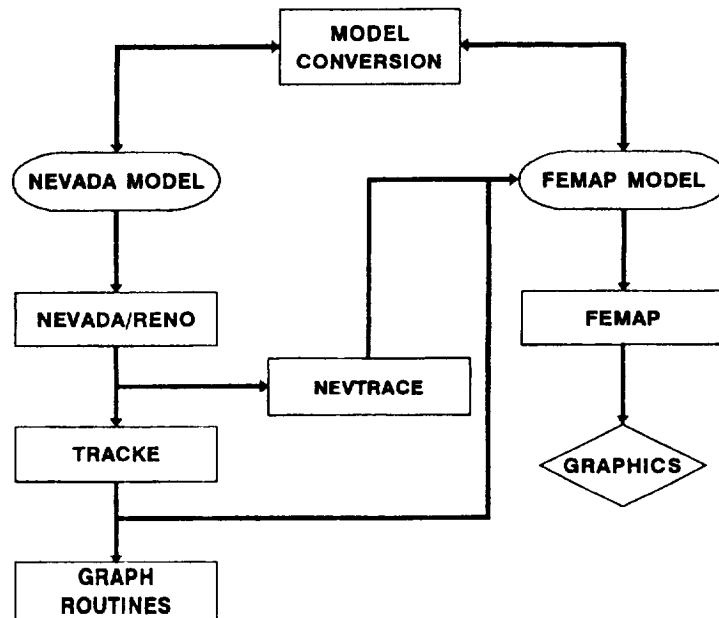
A RAY TRACING PROCEDURE USED AT LeRC

A RAY TRACING PROCEDURE USED AT LeRC

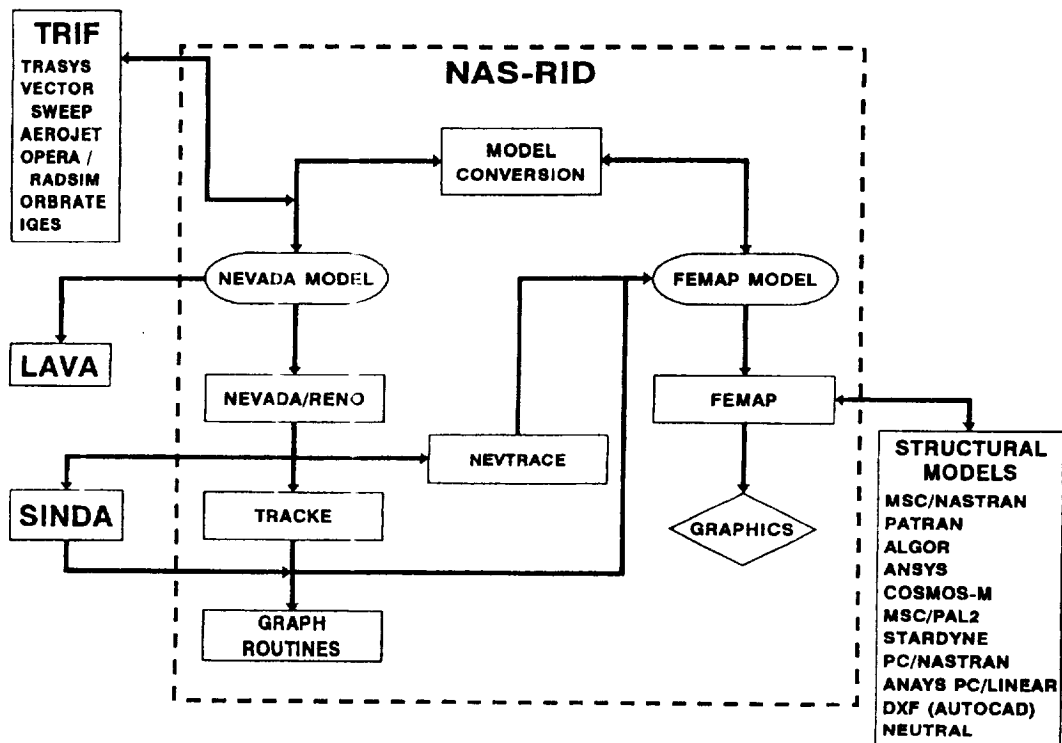
DEVELOPED: NAS-RID (NASA RADIATION IDENTIFICATION PROGRAM)

- **COLLECTION OF PROGRAMS**
 - **MODEL CONVERSION ROUTINES**
 - **NASA LeRC FORTRAN PROGRAMS**
 - **COMMERCIAL PROGRAMS**
 - **PRE AND POST PROCESSING (COLOR 3-D GRAPHICS)**

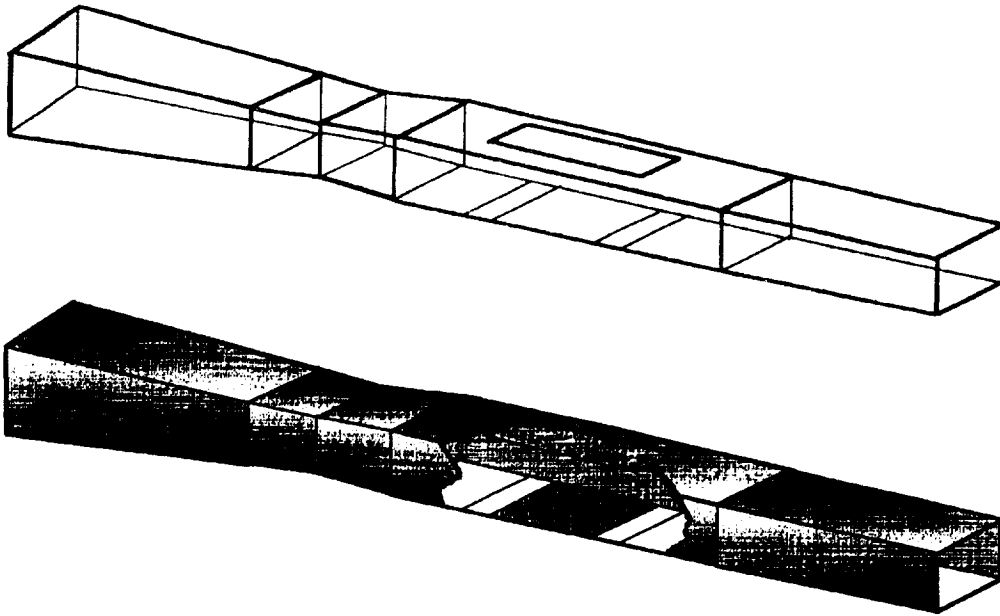
THE NASA RADIATION IDENTIFICATION PROGRAM (NAS-RID)



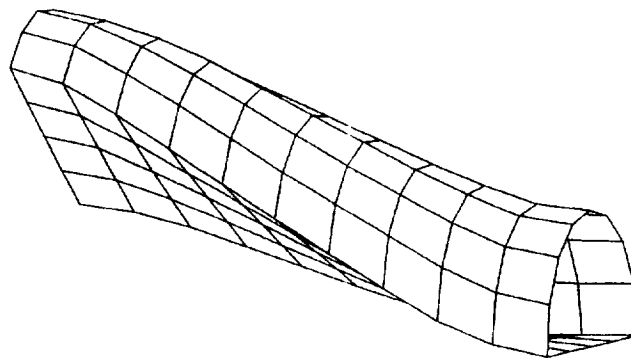
NAS-RID WORKING ENVIRONMENT

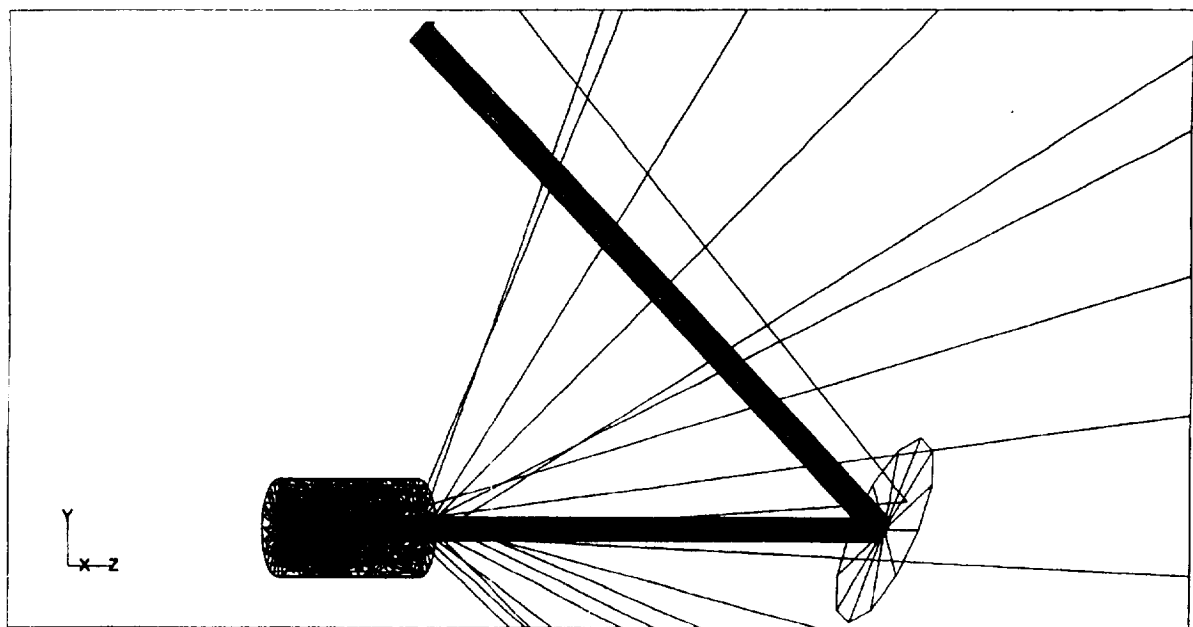
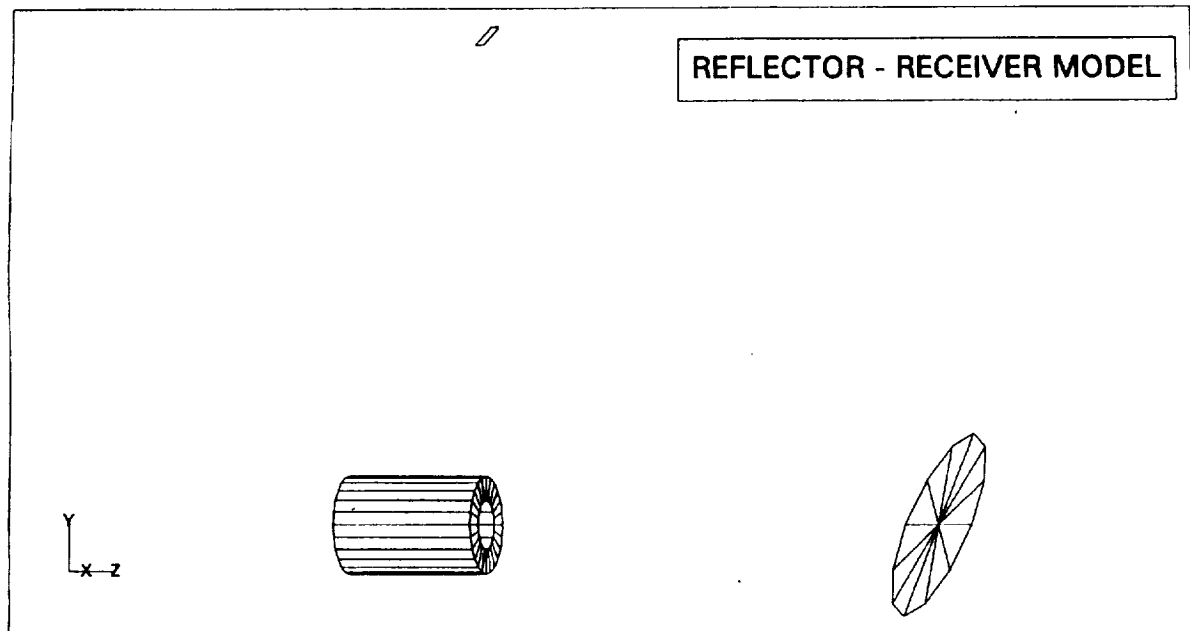


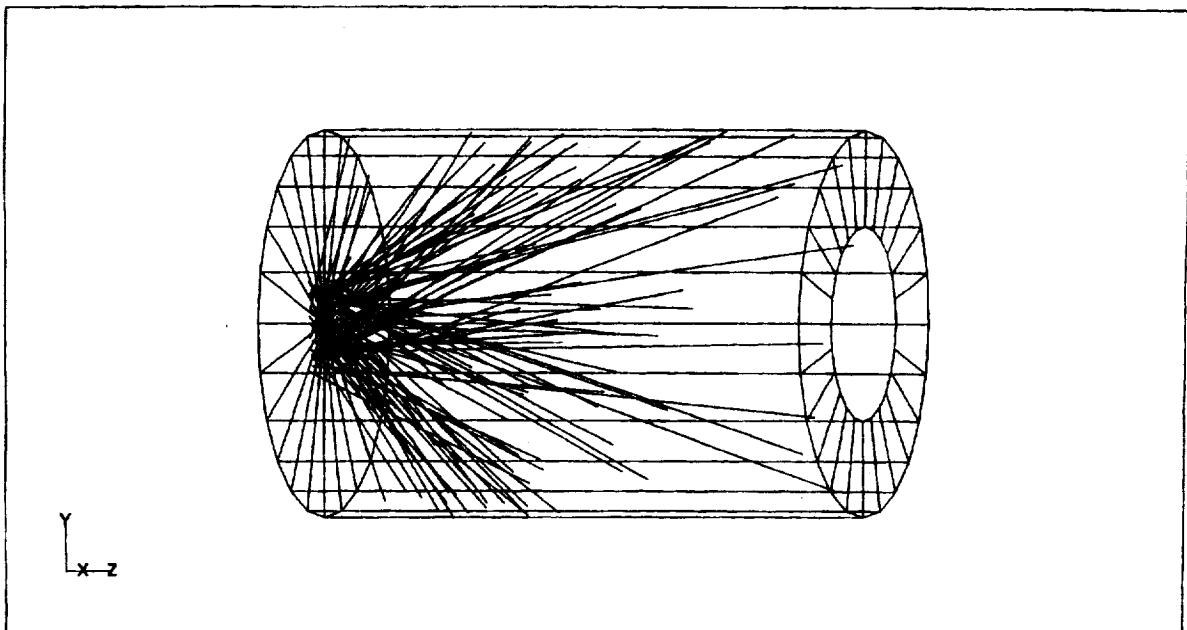
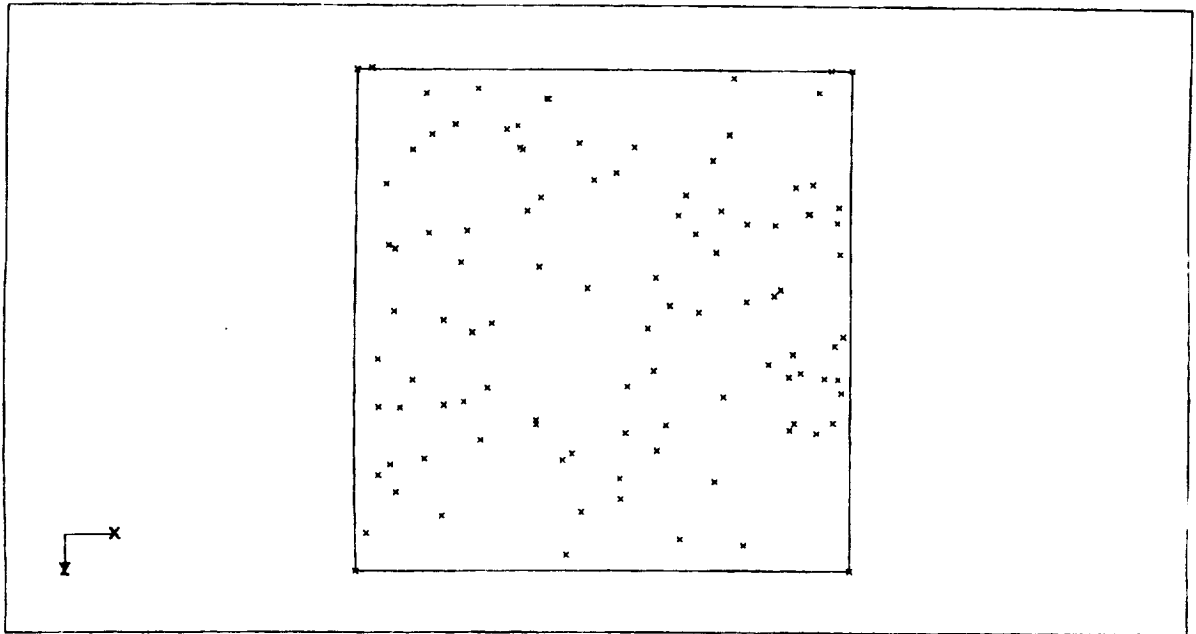
Advanced Film Cooling Test Rig (Radiation Analysis Model)

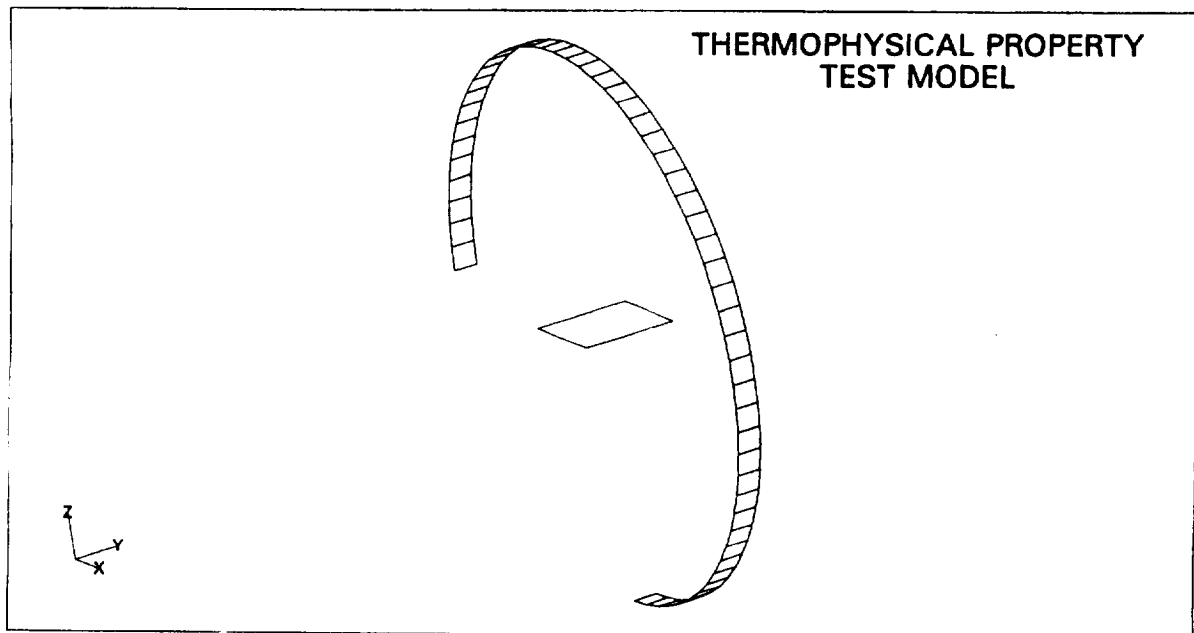
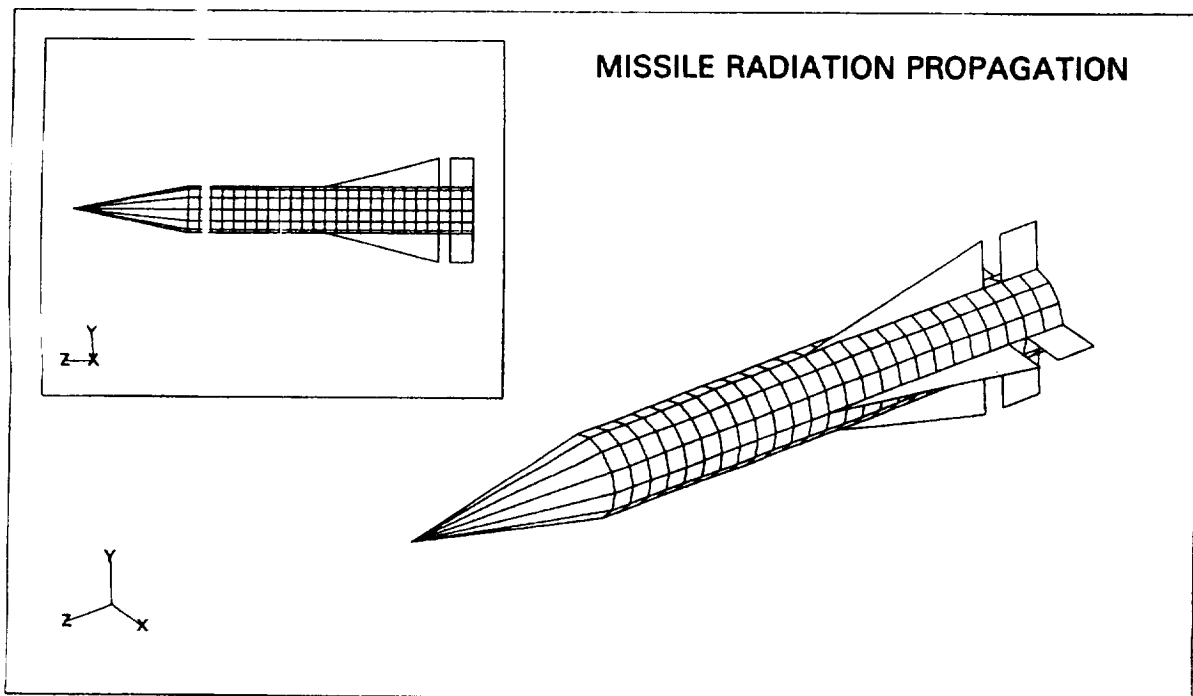


CAVITY RADIATION PROPAGATION

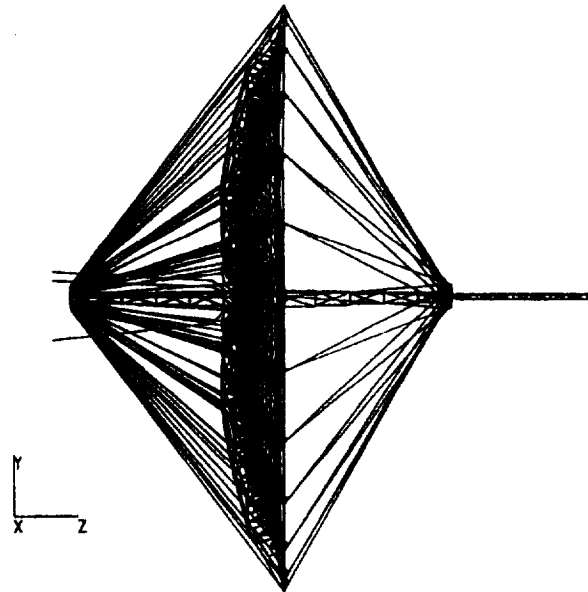




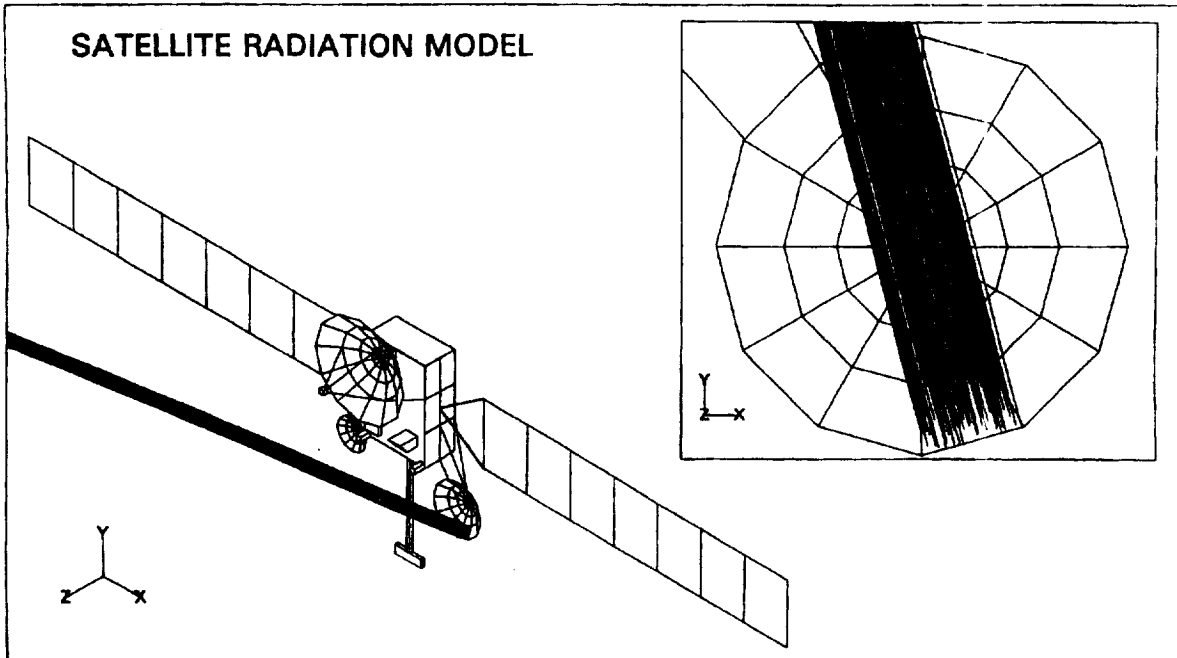




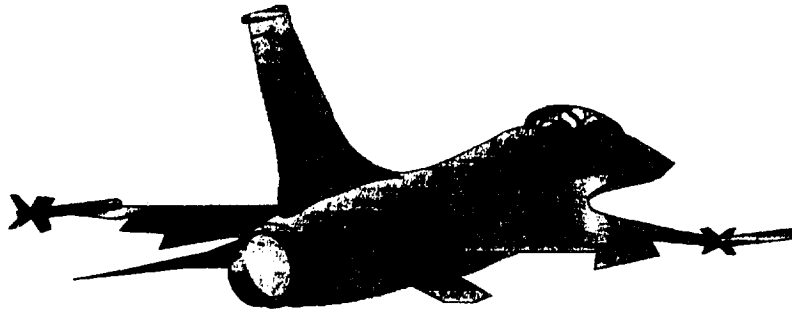
LARGE ANTENNA MODEL



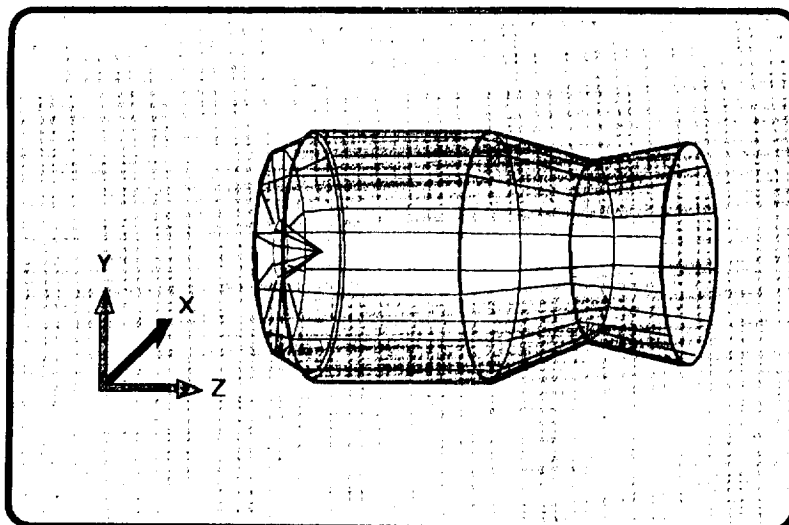
SATELLITE RADIATION MODEL



Aircraft Infrared Radiation Sources



Surface Geometry of Sample Cavity Model



COMPUTER DEMOS

A variety of models and results are displayed using the programs associated with NASA Radiation Identification Program (NAS-RID). The computer demos show graphic model generation, pre and post processing of results, and animation. The computer demos show a variety of options that aid the uses and provide graphic visualization for results interpretation.

RUN COMPUTER DEMOS

**FEMAP
NEVTRACE
LAVA**

INTRODUCTION TO RAY TRACING PROGRAMS

There are a variety of ray tracing programs used to analyze the propagation of absorbing and non-absorbing radiation. At this time two programs, NEVADA and TSS (ref. 10) are discussed. Each program has advantages and disadvantages based on analysis functions, graphics, computer requirements, post processing, validation procedures, and user support. Typical ray tracing operations and features are discussed. An input file for the NEVADA program will be discussed and several examples given. For additional information regarding inputs, options, and results, refer to the NEVADA or TSS user manuals.

INTRODUCTION TO RAY TRACING PROGRAMS

RAY TRACING PROGRAMS METHOD OF ANALYSIS

TYPICAL PROGRAM OPERATIONS:

- A MONTE-CARLO TECHNIQUE IS APPLIED TO A RAY TRACING PROCEDURE TO MODEL RADIATION EXCHANGE.
- THE RAY TRACING PROCEDURE MATHEMATICALLY TRACES EMITTED RAYS (SIMULATING EMITTED RADIATION) AS THEY PROPAGATE.
- EACH RAY IS CONSIDERED A BUNDLE OF PHOTONS.
- BUNDLES INTERACT WITH VARIOUS SURFACES
 - REDUCING ITS ENERGY LEVEL
 - SURFACE PROPERTIES AFFECTING BUNDLE'S PROPAGATION
- BY ACCOUNTING, PERCENTAGES OF INCIDENT AND ABSORBED ENERGY ARE COMPUTED.

TYPICAL FEATURES OF RAY TRACING PROGRAMS

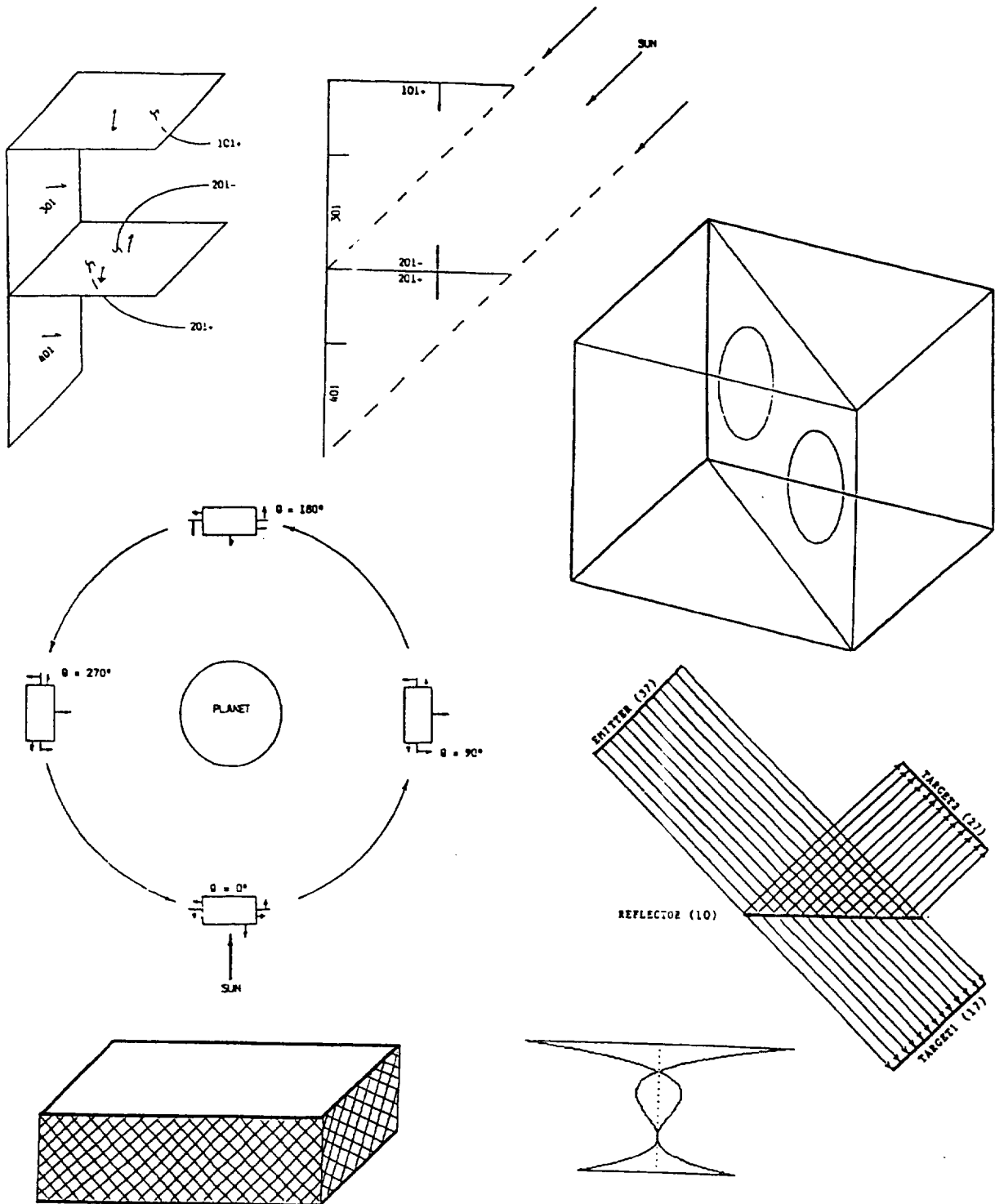
- ANALYZE DIRECT AND REFLECTED RADIANT ENERGY
- EMIT RAYS
 - LAMBERTIAN DISTRIBUTION
 - ORTHOGONAL
 - DIRECTION DEFINED
- DIFFUSE OR SPECULAR SURFACES
- SURFACES PROPERTIES AS A FUNCTION OF ANGLE INCIDENCE
- TRANSMITTANCE / REFRACTION
- SUN / EARTH RADIANT SOURCES
- LARGE MODELS
- BI-DIRECTIONAL REFLECTANCE
- PARTICIPATING / ABSORBING MEDIA
- DIVERGENT / COLLIMATED SOLAR SOURCE

STANDARD RAY TRACING HEAT TRANSFER CODES

STANDARD RAY TRACING CODES USED IN PREDICTING RADIATION INTERCHANGE FACTORS AND ENVIRONMENTAL RADIANT HEATING SOURCES:

- NEVADA
(NET ENERGY VERIFICATION AND DETERMINATION ANALYZER)
- TSS
(THERMAL SYNTHESIZER SYSTEM)

NEVADA MANUAL SAMPLE PROBLEMS



SUMMARY

The summary section provides several general comments regarding ray tracing analysis techniques. The summary section is also used to display information regarding the computer programs ownership, obtainability, cost, and availability. Do to the constant change of this information, these figures have been omitted.

SUMMARY

- RAY TRACING APPLICATIONS APPLIES TO:
 - BASIC RESEARCH
 - DESIGN
 - DEVELOPMENT
- RAY TRACING APPROACH CAN APPLY TO MULTIPLE ENGINEERING DISCIPLINES
- RAY TRACING SOLUTIONS REQUIRE:
 - EXPERIENCE AND JUDGEMENT
 - DIVERSE BACKGROUND
 - CREATIVITY

COMPANY TRADEMARKS

NEVADA	TURNER ASSOCIATES CONSULTANTS
TSS	NASA, LYNDON B. JOHNSON SPACE CENTER
TRASYS	MARTIN MARIETTA
VECTOR SWEEP	GENERAL DYNAMICS
AEROJET	AEROJET
OPERA/RADSIM	THE BOEING COMPANY
ORBRATE	THE LOCKHEED MISSILE & SPACE COMPANY
IGES	U.S. DEPARTMENT OF COMMERCE, NATIONAL BUREAU OF STANDARDS
TRIF	THE AEROSPACE CORPORATION
NAS-RID	NASA, LEWIS RESEARCH CENTER
LAVA	THE AEROSPACE CORPORATION
SINDA	NETWORK ANALYSIS ASSOCIATES INC. / MARTIN MARIETTA
FEMAP	ENTERPRISE SOFTWARE PRODUCTS
MSC/NASTRAN	THE MacNEAL-SCHWENDLER CORPORATION
PC/NASTRAN	THOROUGHbred SOFTWARE, INC.
PATRAN	PDA ENGINEERING
ALGOR	ALGOR INTERACTIVE SYSTEMS, INC.
ANSYS	SWANSON ANALYSIS SYSTEMS INC.
ANSYS PC/LINEAR	SWANSON ANALYSIS SYSTEM INC.
COSMOS-M	STRUCTURAL RESEARCH AND ANALYSIS CORPORATION
MSC/PAL2	THE MacNEAL-SCHWENDLER CORPORATION
STARDYNE	STARDYNE DIV. OF GENERAL MICROELECTRONICS CORP.
DXF (AUTOCAD)	AUTODESK, INC.

Concluding Remarks

The ray tracing analysis terminology and solution process was introduced to provide insight into radiation heat transfer applications. This collection of figures displayed the capabilities and procedures used in ray tracing techniques as compared to other analytical approaches for radiation propagation calculations. Ray tracing programs can provide enhanced capabilities basis on performance, accuracy and flexibility to solve both simple and complex problems. Ray tracing provides the user a tool for developing thermal design experience and engineering judgment through analysis experimentation, while using minimal computer resources and computational time. By comparing the advantages and disadvantages between ray tracing and analytical methods, an understanding between the methods becomes evident.

A thermal analysis working environment was introduced to solve radiation heat transfer problems based on ray tracing. The NASA Radiation Identification Program (NAS-RID) was developed to solve the most demanding radiation heat transfer problems by incorporating the physics of radiation propagation, provide color model and solution graphics, and supply various model conversion capabilities. The thermal analysis environment was designed to manage the components of a radiation heat transfer problem on a personal-computer, but also transfer large computer intense problems to a mainframe or super computer. This working environment requires limited or minimal computer resources. The NAS-RID analysis environment combines several commercial and NASA developed computer codes within a non-rigid or open structure that brings certain advantages to the thermal user. By introducing the NAS-RID analysis environment, it may provide insight into various available analysis tools and serve as a baseline reference for designing and building ones own solution analysis environment.

Appendix A - Basic Radiation Heat Transfer Concepts

The following discussion briefly introduces some basic radiation heat transfer concepts. These radiation heat transfer concepts are used to define the solution techniques and requirements for use in NAS-RID. The basic definitions, equations, units, and notation used to define the radiation characteristics were selected from reference 1.

The simplest mode of radiation heat transfer occurs when energy is emitted from a single flat surface in a vacuum where no reflected energy is involved. If the surface is a perfect absorber and emitter of radiant energy, it is called a blackbody. This blackbody also emits the maximum amount of radiant energy to its surrounding hemisphere. The intensity of radiation emitted by a blackbody in any direction for a single wavelength is defined by Planck's Law as:

$$i'_{\lambda b}(\lambda, T) = \frac{2C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \left[\frac{BTU}{hr \mu m ft^2 sr} \right] \quad (A1)$$

where C_1 and C_2 represent Planck's spectral energy distribution constants, as shown:

$$C_1 = hC_o^2 \quad C_2 = \frac{hC_o}{k}$$

$$C_1 = .18878 \times 10^8 \frac{BTU \mu m^4}{hr ft^2} \quad C_2 = 25897.84 \mu m ^\circ R$$

The prime notation defines a directional quantity of radiation per unit solid angle for a single direction. The subscripted terms specify the quantity as spectral (λ - one wavelength), and the surface as a blackbody (b). The dependent variables are listed in the parentheses. The emissive power radiated from a blackbody over an entire hemisphere in a vacuum at a particular wavelength is defined as:

$$e_{\lambda b}(\lambda, T) = \pi i'_{\lambda b}(\lambda, T) = \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \left[\frac{BTU}{hr \mu m ft^2} \right] \quad (A2)$$

By integrating equation (A2) over the entire wavelength band, the total blackbody hemispherical emissive power at a specific surface temperature is then:

$$\begin{aligned}
e_b(T) &= \int_0^{\infty} e_{\lambda b} d(\lambda) = \int_0^{\infty} \pi i_{\lambda b} d(\lambda) = \int_0^{\infty} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda) \\
&= \sigma T_A^4 \left[\frac{BTU}{hr \ ft^2} \right]
\end{aligned} \tag{A3}$$

where σ represents the Stefan-Boltzmann constant:

$$\sigma = 0.17123 \times 10^{-8} \left[\frac{BTU}{hr \ ft^2 \ ^\circ R^4} \right]$$

Applying the emitting surface area to equation (A3) gives the total blackbody hemispherical emitted energy per unit time as:

$$E_{b \ A_1}(T_A) = \int_0^{\infty} A_1 e_{\lambda b}(\lambda) d\lambda = A_1 \sigma T_A^4 \left[\frac{BTU}{hr} \right] \tag{A4}$$

For a real (non-blackbody) surface, thermophysical properties control the radiant energy absorbed, emitted, and reflected from the surface. These properties can be a function of incident and reflected angles, wavelength, and temperature. Frequently, several simplifying assumptions can be made regarding the surface thermophysical properties. Averaged surface properties may be derived if one can average over all directions and wavelength bands. Applying these assumptions, a surface that absorbs and emits a fixed fraction of radiation from any direction and at any wavelength is now defined as a diffuse gray surface. The directional and spectral absorptivity and emissivity then become:

$$\epsilon'_{\lambda}(\theta, \phi, \lambda, T_A) = \epsilon_A(T_A)$$

$$\alpha'_{\lambda}(\theta, \phi, \lambda, T_A) = \alpha_A(T_A)$$

From Kirchhoff's law the directional, spectral and hemispherical total values of absorptivity and emissivity are equal, thus:

$$\epsilon(T_A) = \alpha(T_A) \tag{A5}$$

The dependence of the surface temperature on the surface emissivity value also may be averaged over the radiation heat transfer band.

Applying surface thermophysical properties results in the surface being defined as a non-blackbody. The total non-blackbody (diffuse-gray) hemispherical emissive power is:

$$e(T_A) = \int_0^\infty \epsilon_A e_{\lambda b}(\lambda) d\lambda = \epsilon_A \sigma T_A^4 \left[\frac{BTU}{hr ft^2} \right] \quad (A6)$$

The total non-blackbody hemispherical emitted energy is:

$$E_{A_1}(T_A) = \int_0^\infty A_1 \epsilon_A e_{\lambda b}(\lambda) d\lambda = A_1 \epsilon_A \sigma T_A^4 \left[\frac{BTU}{hr} \right] \quad (A7)$$

For radiation to be exchanged between surfaces, a geometric relationship (geometric configuration factor or view factor) between the surfaces must be defined. The view factor for blackbody isothermal surfaces is the fraction of emitted radiant energy leaving a surface i that reaches another surface j . Since both surfaces are blackbodies or perfect absorbers of radiant energy, no reflected energy is introduced into the view factor value, F_{i-j} . The total blackbody emitted energy from surface A_1 that is incident and absorbed by surface A_2 is then:

$$E_{b A_1 - A_2}(T_A) = A_1 F_{A_1 - A_2} \sigma (T_{A_1}^4) \left[\frac{BTU}{hr} \right] \quad (A8)$$

For simple geometric configurations various view factor references are available. For complex geometric configurations, various computer techniques have been developed where the surfaces are defined, and mathematical or ray tracing techniques are applied to solve the surface relationships.

For non-blackbody surfaces the blackbody view factor is replaced by the radiation interchange factor, B_{i-j} , which represents real surface radiation exchange. The radiation interchange factor is the fraction of emitted energy by a real surface i that is absorbed by real surface j , including all reflections from other real surfaces including the emitting surface i . Computer programs are also available to calculate B_{i-j} values. For the radiation exchange between two real surfaces, defined as A_1 and A_2 , the total non-blackbody emitted energy from surface A_1 that is absorbed by surface A_2 is:

$$E_{A_1 - A_2}(T_{A_1}) = A_1 B_{A_1 - A_2} \epsilon_{A_1} \sigma T_{A_1}^4 \left[\frac{BTU}{hr} \right] \quad (A9)$$

This is where the B_{i-j} term defines the relationship between the energy emitted from surface A_1 that is absorbed by surface A_2 directly and indirectly. This indirect radiant energy may be in the form of multiple reflecting energy between A_1 and A_2 , and energy from A_1 that is reflected from other surfaces to A_2 . The radiation path for a multiple surface cavity configuration may include all surfaces, which can result in a large number of total non-blackbody emitted energy terms:

$$\text{Energy Transfer From All Possible Radiation Paths} = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \epsilon_i \sigma A_i B_{i-j}$$

The radiation exchange also can be evaluated within a particular wavelength region or fraction of the total emissivity power. This is done by simply using the total blackbody hemispherical emissive power, equation (A3), and modifying the limits of integration as shown:

$$e_b(\lambda_1 T \rightarrow \lambda_2 T) = \int_{\lambda_1}^{\lambda_2} e_{\lambda b} d(\lambda) = \int_{\lambda_1}^{\lambda_2} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda) \quad (\text{A10})$$

The non-blackbody hemispherical emitted energy within a wavelength band becomes:

$$E_{A_1}(\lambda_1 T \rightarrow \lambda_2 T) = \epsilon_{A_1} A_{A_1} \int_{\lambda_1}^{\lambda_2} e_{\lambda b} d(\lambda) = \epsilon_{A_1} A_{A_1} \int_{\lambda_1}^{\lambda_2} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda) \quad (\text{A11})$$

Applying the radiation interchange factor results in the non-blackbody emitted energy from individual surfaces within a wavelength band:

$$E_{A_1-A_2}(\lambda_1 T \rightarrow \lambda_2 T) = \epsilon_{A_1} A_{A_1} B_{A_1-A_2} \int_{\lambda_1}^{\lambda_2} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d(\lambda) \quad (\text{A12})$$

The integration term can be solved using a numerical polynomial curve fit resulting in the total non-blackbody hemispherical emitted energy equation as:

$$E_{A_1-A_2}(\lambda_1 T \rightarrow \lambda_2 T) = \epsilon_{A_1} A_{A_1} B_{A_1-A_2} [\Gamma_{0-\lambda_2 T_{A_1}} - \Gamma_{0-\lambda_1 T_{A_1}}] \sigma T_{A_1}^4 \left[\frac{BTU}{hr} \right] \quad (\text{A13})$$

where the $\Gamma_{0-\lambda T}$ is represented as:

$$\Gamma_{0-\lambda T} = \frac{15}{\pi^4} \sum_{n=1}^{\infty} \left[\frac{e^{-nx}}{n} \left(x^3 + \frac{3x^2}{n} + \frac{6x}{n^2} + \frac{6}{n^3} \right) \right] \quad (\text{A14})$$

$$\text{where } x = \frac{C_2}{\lambda T}$$

Tabulated values of these polynomial approximations are also available as a function of wavelength-temperature products in reference 1.

Appendix B - Model Definition

Model

The term "model" represents a data set that contains required information that defines the physical attributes of a geometry for analysis. A model supplies parameters that represent the physical geometry, surface thermophysical properties, and solution requirements. The geometry is subdivided into a number of finite surfaces called nodes for geometric math models. The actual number of nodes and their geometry depends on the desired model representation, accuracy of results, structural design considerations, computer capabilities, and computer computational time requirements. Each node represents an average surface temperature defined over the entire surface. Using the ray tracing approach, restrictions on uniform node energy distributions (radiosity and irradiation) may be eliminated (ref. 3).

References

1. Siegel, R., and Howell, J.R.: "Thermal Radiation Heat Transfer", Second ed., Hemisphere Publishing Corporation, Washington, DC, 1981.
2. Turner, R.C.: "NEVADA Software Package User's Manual", Twelfth Edition, Ver. 17, Turner Associates Consultants, 1988.
3. Baumeister, J.F.: "Thermal Radiation Characteristics of Non-Isothermal Cylindrical Enclosures Using a Numerical Ray Tracing Technique", NASA TM-102527, 1990.
4. 1990, "FEMAP User's Manual", Version 3.1, Enterprise Software Products.
5. Evans, Nystrom, Pollack, 1987, "Thermal Radiation Interchange Format (TRIF)", Report No. ATR-86A(9975)-2, The Aerospace Corporation.
6. 1990, "Lava User's Guide", Version 1.0 Rough Draft, The Aerospace Corporation.
7. Gaski, J.D., 1987, "SINDA User's Manual", Network Analysis Associates, Inc.
8. Kneizys, F.X., 1988, "Users Guide to LOWTRAN 7", AFGL-TR-88-0177, Air Force Geophysics Laboratory.
9. Hecht, E., and Zajac, A.: "Optics", Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1979.
10. 1992, "User Manual, Thermal Synthesizer System", Lockheed Missiles and Space Company, Inc., Sunnyvale, California, LMSC/F191409.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE August 1993		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE Application of Ray Tracing in Radiation Heat Transfer			5. FUNDING NUMBERS	
6. AUTHOR(S) Joseph F. Baumeister				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-7915	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-106206	
11. SUPPLEMENTARY NOTES Prepared for the Computer Applications Symposium cosponsored by the ASME and LMU Los Angeles, California, March 12, 1993, and Thermal and Fluids Analysis Workshop sponsored by NASA Lewis Research Center, Cleveland, Ohio, August 16-20, 1993.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 34			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This collection of presentation figures displays the capabilities of ray tracing for radiation propagation calculations as compared to an analytical approach. The goal is to introduce the terminology and solution process used in ray tracing, and provide insight into radiation heat transfer principles and analysis tools. A thermal analysis working environment is introduced that solves demanding radiation heat transfer problems based on ray tracing. This information may serve as a reference for designing and building one's own analysis environment.				
14. SUBJECT TERMS Radiation heat transfer; Ray tracing			15. NUMBER OF PAGES 52	
			16. PRICE CODE A04	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	